Quantifying Soil Carbon Storage in the Farm Carbon Story

Report by

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December 2009

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Summary

The Farm Carbon Story uses information which is already routinely compiled as part of a well delivered property management plan such as a farm map, soil types and land use areas, as the basis for summarising the overall ‘carbon picture’ of the farm. It is designed to present the farmer with the ‘big picture’ of carbon stores and fluxes on their farm rather than just their emissions and sequestrations which are the focus of current carbon accounting using existing carbon calculators. Currently available carbon calculators use information relevant at regional scales rather than farm or paddock scales.

The measured farm soil carbon stores in the upper 30 cm of soil were 371 to 702 T/ha CO_2 equivalents across the three farms assessed in this pilot. The highest value occurred on predominantly Red Dermosol and Ferrosol soils, which have high clay contents, are under perennial irrigated pasture for dairying, and have a mean annual rainfall of 1242 mm. The lower soil carbon stores occurred on Kurosols, Sodosols and Tensols which have sandy loam surface textures, are used for cropping and have mean annual rainfalls of 560 – 760 mm. The largest property (753 ha) and had the greatest soil carbon store (302,300 T CO_2 equivalents) but the smallest property (305 ha) had a greater soil carbon store (214,463 T CO_2 equivalents) than the 460 ha property (170,454 T CO_2 equivalents) due to a combination of soil type, land use and climate.

The total farm carbon stores are much larger (i.e. 1000 x greater) than modelled annual emissions or sequestrations. The sequestration of carbon under current cropping rotations ranged from 0.13 T CO_2 /ha/yr to 0.55 T CO_2 /ha/yr on sandy loam textured soils. Under perennial pasture, emission of 0.45 T CO_2 /ha/yr was modelled on a clay loam textured soil with initially high soil carbon, to sequestration of 1.03 T CO_2 /ha/yr on a sandy loam textured soil. Modelling of the influence of management on soil carbon indicates that farmers can influence whether they emit or sequester soil carbon on an annual basis. The sequestration of soil carbon under current management is relatively small but may be off set against emissions generated by usage of fuel, electricity or fertiliser. Sequestration rather than emission should be interpreted as indicating that current management is sustainable over the medium to long term in terms of soil carbon. This study demonstrates that farmers are custodians of a large ‘bank’ of soil carbon which is susceptible to degradation and conversion into CO_2 if management is not sustainable.

Agronomic soil test values of soil carbon contents less than 5.5 % were similar to those determined by more detailed sampling used in this study. Consequently, the agronomic soil test values are considered to be suitable for use in models such as Black Magic, as long as they are adjusted to depths used in the modelling.

The calculated farm carbon storage in the upper 30 cm of soils varied depending on the scale of investigation. Broad scale assessment using ASRIS information ranged from being 25 - 82% less than that determined from farm scale information. The differences are disturbingly large and indicate that the use of currently available broad scale information can lead to large errors in calculating farm soil carbon storage. The result is perhaps unsurprising given that the ASRIS data is of relatively small resolution. It must be emphasized that this study sampled three farms in the north and northeast of Tasmania. Additional sampling from other locations, where there are a range of soil types encompassing other land use types and topography, would further contribute to improving the estimates of the amount of carbon held on farms in Tasmania.

1. Introduction

Recent concern over the extent of global warming and the contribution made by agriculture has lead to interest in soil carbon as a potential store of atmospheric carbon. Soil carbon is an important component of the global carbon cycle, accounting for between two-thirds and three-quarters of the terrestrial carbon store (Frogbrook *et al*. 2009). As soils contain significantly more carbon than is present as carbon dioxide (CO_2) in the atmosphere, the stability of this soil store is a major source of uncertainty in future climate change predictions.

Under the Kyoto Protocol, an agreement made under the United Nations Framework Convention on Climate Change, signatory nations have to produce accurate estimates of their carbon store and monitor changes with time. Several approaches have been used to estimate terrestrial carbon stores and many studies have used a combination of soil and vegetation groups, land cover and model predictions. There is increasing pressure and demand for estimates of current soil organic carbon stocks as well for information on how different farming enterprises can be managed in order to minimise their carbon footprint. It is important, however, that accurate and reliable data are used as the basis for these estimates otherwise they will be in error.

The Farm Carbon Story uses the farm map as the basis for summarising the overall 'carbon picture' of the farm. It is designed to present the farmer with the 'big picture' of carbon stores and fluxes on their farm rather than just their emissions and sequestrations which are the focus of current carbon accounting using existing carbon calculators.

The Farm Carbon Story approach uses information which is already routinely compiled as part of a well delivered property management plan (PMP) eg. farm map, soil types, land use areas (cropping, native bush, grasslands etc). Currently available carbon calculators use information relevant at regional scales (eg. tree growth curves) rather than farm or paddock scales. Consequently minor changes in data inputs have limited impact on the overall big picture and the outputs can be misleading to farmers.

The farmers involved in this study want to see this approach used to demonstrate the valuable role that farmers play as 'carbon stewards'. They believe that better recognition should be given by the community and politicians for the large carbon reserves stored by farmers through good land management practices such as good crop rotations, permanent pastures, cover crops and minimal fallows, preserved native grasslands, remnant bush, and planting of shelterbelts. The farmers want to counter media portrayal of farmers as major carbon polluters because of livestock emissions.

Soil organic carbon is both a source and a sink of greenhouse gases. Emissions typically occur after clearing and tillage, while some land management practices, such as improved pasture and minimum tillage, may increase soil organic carbon. The largest concentrations of soil carbon are generally found in the uppermost layers of the soil since this is where the bulk of organic inputs occur, although the distribution of soil carbon through the soil profile is determined by a range of factors. The overall quantity of organic carbon in a given soil is determined largely by climate, clay content and organic inputs, but can also be significantly affected by land-use. For example, soil organic carbon is usually greater under forest and pasture than areas of cropping although considerable variation also exists within these broad land use types.

This 'Proof of Concept Farm Carbon Story' project is part of a contract to be delivered to NRM North and is funded by the Australian Government.

2. Project components

There were 4 components in this investigation:

a) Measure current on-farm soil carbon stores by physical measurement.

b) Compare different scales of assessment of farm carbon storage.

   The number of polygons mapped on the individual farm properties was far greater at the farm scale (12-24) than at the regional scale (1-2). We wanted to test whether the difference in scale of assessment would have any effect on the estimates of farm carbon stores.

c) Assess the impact of current and changed land management on soil carbon.

   The impact of current management practices on the carbon balance under current and planned future land uses on the selected farms was explored using a modelling approach. Running appropriate current and future scenarios through the BlackMagic soil carbon model allowed farmers to easily understand the effect of different scenarios on carbon emissions and sequestrations and identify opportunities for improving management practices.

d) Compare specific soil carbon sampling results with agronomic soil test results.

   Our aim was to compare results from routine farm agronomy soil testing with detailed soil sampling specifically undertaken for soil carbon analysis in order to be able to define error margins for future use. As part of future PMP delivery, it is not economical to undertake detailed soil carbon tests for all land use types on a farm and so we want to be able to enter existing farm soil tests into the Black Magic model and understand the error margins in relation to the interpretation of the overall farm carbon picture.

3. Pilot farms

The three pilot farms used in this study are representative of enterprise types in Tasmania and the range of issues that are seen in PMP delivery.

a) 'Armidale', owned by the Wishaw family, is a mixed enterprise property near Carrick with diverse enterprises including a horse stud, sheep and cattle grazing plus intensive and extensive cropping rotations (Figure 1). The farm has significant woody weed infestations (gorse, willows, hawthorn) (Figure 2) which are common challenges in the debate on carbon sequestration v's NRM management.

Figure 1. Looking southwest from the river floodplain on 'Armidale'.

Figure 2. Woody weeds on 'Armidale'

b) 'Ravenscroft', owned by Cheryl McCartie and Theo Van Brecht, is a dairy farm under permanent pasture and with limited cropping. The farm is located near Ringarooma and has a range of soil types and topography (Figure 3). The farm has some steep bush/weedy areas with potential as carbon offset sites. It is surrounded by plantations (Figure 4) and so plantation land use can be incorporated as a 'property purchase' scenario.

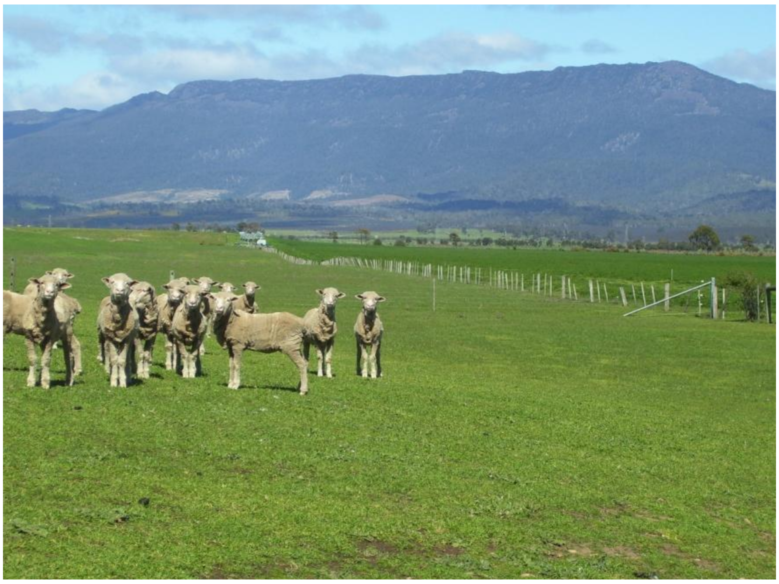
Figure 3. Rolling topography on 'Ravenscroft'.

Figure 4. Plantations on the western boundary of 'Ravenscroft'.

c) ‘Stewarton’, owned by the Walch family, is a mixed enterprise property near Epping Forest with a range of soil types, native grasslands, post-1990 mixed tree and shrub species plantings and plans for further irrigation developments. Intensive and extensive cropping rotations are used (Figure 5) together with sheep grazing (Figure 6).

Figure 5. Intensive cropping under centre pivot irrigation on ‘Stewarton’.

Figure 6. Sheep grazing on improved pastures and irrigated lucerne on ‘Stewarton’.



4. Methods

4.1 Farm soil carbon stores

Seventeen sites were selected on each of the three farms. These sites were representative of the soils and topography previously mapped on the properties. Not all mapped polygons were sampled and some large polygons or soils with multiple polygons had multiple samples taken.

Measurement of soil carbon was undertaken according to the protocols of McKenzie and Dixon (2006). Sampling was carried out in September, which was in late winter/early spring and was during the period of minimum biological activity. Samples were collected in areas sufficiently far from fence lines, gateways and headlands to avoid these edge effects. Five soil cores were taken along a 60 m transect using a 50 mm diameter push auger. Cores were combined to form a single composite specimen for each of 3 depths, 0-50 mm, 50-100 mm and 100 – 300 mm. These samples were dried at 40°C for at least 48 hours, ground to pass a 2 mm sieve, and stored in air-tight containers. The samples were then sent to CSBP Laboratories in Perth, Western Australia, for analysis of total carbon using the Leco dry combustion method. This piece of equipment directly measures the total amount of carbon in a soil sample and is CSIRO's preferred method of soil carbon determination. As the soils in the study areas do not contain large amounts of carbonates (either geologically or from agricultural additions), losses other than organic carbon during this analysis were unlikely.

Bulk density was measured at the sampling site in order to calculate the mass of soil organic carbon (area and depth). Stainless steel cylinders, 60 mm long and 60 mm in diameter, were hammered into the soil at the starting point of the composite sampling transect. Cores were collected from 0-60 mm, 50-110 mm and 150-210 mm depth. Cores with soil intact were excavated and trimmed before the contents were emptied into plastic bags, dried at 105°C, and then weighed. Dry bulk density (BD) was calculated as:

$$\text{BD (T/m}^3\text{)} = \text{Dry weight (T) / Volume (m}^3\text{)}$$

The mass of Carbon stored at each sampling depth, to a total depth of 30 cm, was calculated and converted to a carbon dioxide equivalent by multiplying by 44/12. This carbon dioxide mass value was then multiplied by the area of mapped polygons of each soil type occurring on the farm and the totals summed for the entire farm property (Appendix 2).

4.2 Scale of assessment of farm carbon storage

Assessment of farm carbon stores was compared using the farm scale maps and regional scale information on the Australian soil resource information system (ASRIS) which is accessible via the web (available at: http://www.asris.csiro.au). Farm scale information used for 'Ravenscroft' was 1:25 000 scale land capability at subclass and unit level (Eldridge 1998), for 'Armidale' it was 1:10 000 scale land capability at subclass and unit level (Chilvers 2007), and for 'Stewarton' it was a combination of 1:10 000 scale (Chilvers 1998) and 1:100 000 scale (Doyle 1993) soil type or complex mapping. Land capability units identify areas of land of similar land class and subclass which require similar management and conservation measures, have similar potential productivity and are able to support the same range of crops. Such areas are likely to have similar soils, geology, slope range, and climatic range. Where any individual factor changes sufficiently to alter the management requirements, use or productivity of the land, a new capability unit is mapped (Grose 1999). Unit numbers conventionally are ranked in order from best to worse within a particular capability class (i.e. land with higher productivity and fewer limitations is given a higher land capability unit ranking than land with lower productivity and more severe limitations - thus 4e1 is better than 4e2). The mass of carbon was calculated on per hectare basis using the data collected from the 17 sites on each farm. These values were then multiplied by the by the mapped areas of the soils or land capability units they represent to give a total farm carbon store.

ASRIS provides detailed information on soil properties for areas where mapping has been completed. A consistent set of land qualities are described for land-unit tracts which relate to the intrinsic capability of land to support various land uses – the land qualities relate to soil depth, water storage, permeability, fertility, and erodibility. Soil attribution for ASRIS in Tasmania has been completed for the North West and North East regions providing soil information for two thirds of the agricultural land of Tasmania at ASRIS Land district level which is equivalent to a scale of 1:250,000. Information accessed from ASRIS for the 1-2 polygons mapped on each farm included the soil carbon content (%) and bulk density for each layer to a depth of 300 mm. The information provided on ASRIS is an integrated value of soil properties for each polygon, based on up to 6 soil components for each polygon attributed in the database. The mass of carbon was calculated from the ASRIS data on per hectare basis which was then multiplied by the area of farm represented by the corresponding polygon to give a total farm carbon store.

4.3 Impact of current and changed land management on soil carbon

The effects of different management practices on soil carbon were assessed using Black Magic which is a model adapted from "*Roth-C*", a computer model of soil organic carbon change under UK field cropping (Jenkinson 1990) to suit Tasmanian soils, climate and crops (details in Appendix 1). BlackMagic calculates the input of organic matter from the individual crops in a rotation and determines the rate at which organic carbon is oxidised and lost from the soil as carbon dioxide gas. From a known starting point the model can predict future soil organic carbon content.

In the model, soil organic carbon is separated into four active pools: decomposable plant material, resistant plant material, microbial biomass and humified organic material. The decomposition rate for each of these pools was determined in a similar fashion to that used in the *RothC* model. The resistant plant material decomposition rate was retained at 0.3 as the Tasmanian climate is more similar to that of the UK where the *RochC* model was verified, rather than the hotter and drier climates used verifying the model with Australian data (Skjemstad *et al.* 2004) where changing the decomposition ratet to 0.15/year gave better agreement with long-term rotation trials in Australia. Inputs to the model were based on Tasmanian cropping practices. Crop yields, from which carbon inputs are determined, may be entered manually although the model provides default values if required. The model contains a database of 28 crops commonly used in Tasmanian cropping rotations. Crops range from the traditional (peas and potatoes) to the more exotic (poppies and pyrethrum). Fourteen different soil / area combinations covering the major cropping situations in Tasmania are recognised, and long-term average rainfall, temperature and evaporation data from 30 observation sites are also contained in the database. This model allows for traditional cultivation or minimum tillage practices (which reduce the rate of decomposition) and the option of irrigation (which increases the rate of decomposition but simultaneously allows for increased inputs from higher crop yields).

The model predicts future soil organic carbon (SOC) content for any chosen crop rotation. The change in SOC is also displayed graphically along with the relative carbon contribution from the individual crops in the selected cropping rotation. In recognition of the increasing interest in the capacity of soil to sequester carbon and perhaps counter increasing levels of atmospheric CO_2, the model also displays changes in SOC in terms of CO_2 flux to or from the atmosphere.

The model predicts that equilibrium organic carbon values in Tasmania may be higher than in comparable soils in warmer parts of Australia and while the model predictions may seem reassuring, they must be considered tentative because Tasmania has no long-term studies to validate them.

4.4 Comparison of outputs from specific soil carbon sampling with outputs from agronomic soil sampling

The 'Armidale' farm property was used as a case study for this comparison. A series of agronomic soil test results of soil carbon were made available by the owner that allowed for comparison of individual paddock results with the corresponding detailed soil sampling specifically undertaken for soil carbon analysis. The agronomic soil tests were for a range of different sampling depths as they were undertaken by different companies. These included 100 mm, 150 mm and 200 mm depth. No details on the method of soil carbon determination were available for the agronomic soil tests, but it is assumed that they were by the Walkley and Black method (1934). The different soil carbon values were tested for difference using the Student t-test.

5. Results

5.1 Farm soil carbon stores

The soil carbon stored on each of the pilot farms in the upper 30 cm of soil (Tables 1, 2 and 3) was calculated as:

'Armidale'	170,454 T CO_2 equivalents
'Ravenscroft'	214,463 T CO_2 equivalents
'Stewarton'	302,300 T CO_2 equivalents

The farm total soil carbon stores are large (i.e. three orders of magnitude greater or 1000 times) in comparison with values of annual emissions or sequestrations (see section 4.3 *Impact of current and changed management on soil carbon*). This indicates that farmers are custodians of a large amount of soil carbon.

'Stewarton' was the largest property (753 ha) and had the greatest soil carbon store. 'Ravenscroft' was the smallest property (305 ha) but it had a greater soil carbon store than 'Armidale' (460 ha), which is likely to be due to a combination of soil type, land use and climate. The soil carbon stores amount to 371, 702 and 401 T/ha CO_2 equivalents for 'Armidale', 'Ravenscroft' and 'Stewarton' respectively. The highest per hectare value on 'Ravenscroft' occurred on predominantly Red Dermosol and Ferrosol soils, which have high clay contents, are under perennial irrigated pasture for dairying, and have a mean annual rainfall of 1242 mm. 'Armidale' and 'Stewarton' are both dominated by Kurosols, Sodosols and Tensols which have sandy loam surface textures, are used for cropping and have mean annual rainfalls of 766 mm ('Armidale') and 562 mm ('Stewarton).

Under Tasmanian conditions, clay textured soils (Dermosols, Ferrosols, Vertosols) have been found to have greater soil carbon contents than sandy textured soils (Kurosols, Sodosols, Tenosols) and perennial plant systems such as permanent pasture result in greater soil carbon contents than cropping systems due to greater inputs over the long term (Cotching 2009).

The amount of organic matter in a soil depends on a range of factors, and is determined by the balance between accumulation and loss. The main factors are:

Climate – soil carbon tends to be greater in areas of higher rainfall due to greater amounts of plant growth providing greater inputs. Soil organic matter content is greater in areas with cooler temperatures due to reduced rates of breakdown. Tasmania has a relatively wet and cool climate compared to much of mainland Australia and so soil organic matter contents are relatively high.

Soil type – clay helps protect organic matter from breakdown, either by binding organic matter onto the clay or by forming a barrier around organic particles within soil aggregates which limits access to metabolizing organisms. Clay soils in the same area under similar management will tend to retain more organic matter than sandy soils. Hence the sandy Sodosols of the northern midlands have less organic matter than the clay loam Ferrosols regardless of management.

Vegetative growth – the more plant production there is, the greater are the inputs of organic matter. Also, the more woody this vegetation is (greater C:N ratio), the slower it will breakdown leading to greater retention of organic matter.

Tillage – tillage will increase organic matter breakdown by increasing the exposure to air and the metabolism by micro-organisms. However, the impact of tillage is not as great as the effect of other management factors, such as length of fallow and the type of crops, on the amount of organic matter grown and returned to the soil. An exception to this is where tillage leads to increased erosion.

The farm carbon stores calculated are only part of the carbon stored in soils in Tasmania as other data indicates that Tasmanian soils can store as much carbon from 30 cm to 1 m depth as they store from 0 – 30 cm depth. The amounts are variable depending on soil type and environment.

Table 1. Farm soil carbon stores in CO_2 equivalents on 'Armidale' for 0-30 cm depth.

Map unit	Map unit area (ha)	Sample site No.	Carbon dioxide 0-30 cm (T/ha)#	Average Carbon dioxide 0-30 cm (T/ha)	Carbon dioxide in mapped unit 0-30 cm (T)
Armidale					
5e	18.3	1	298	298	5453
4s	165.9	2	359	337	55893
4s		3	296		
4s		4	356		
4s		5	337		
4e2	45.2	6	279	299	13505
4e2		7	318		
4w1	63.2	8	287	288	18175
4w1		9	288		
4w2=4w1	6.2	ns*		288	1783
4e1	50.6	10	389	280	14181
4e1		11	220		
4e1		12	232		
4f	50.4	13	413	485	24443
4f		15	582		
4f		16	460		
5f	59.9	14	760	618	37020
5f		17	476		
Total area (ha)	460			**Farm total (tonnes)**	170454

* not sampled; # see Appendix 2

Table 2. Farm soil carbon stores in CO_2 equivalents on 'Ravenscroft' for 0-30 cm depth.

Map unit	Map unit area (ha)	Sample site No.	Carbon dioxide 0-30 cm (T/ha)#	Average Carbon dioxide 0-30 cm (T/ha)	Carbon dioxide in mapped unit 0-30 cm (T)
Ravenscroft					
3s1	26.7	7	932	932	24884
3c1	51.6	5	649	780	40263
3c1		6	847		
3c1		17	845		
3e2=3c1	2.5	ns		932	2330
3x1 = 3c2	6.7	ns		932	6244
3w1	6.1	16	679	679	4142
4e2	15.3	8	705	705	10787
4e5	63.8	4	599	597	38067
4e5		9	613		
4e5		10	578		
4w1	5.4	11	713	713	3850
4s9=4w1	5.6	ns		713	3993
4w2	4.8	13	640	640	3072
4s1	6.9	14	849	464	3201
5s1	4.7	15	1045	1045	4912
5e1=5e3	10.6	ns		656	6954
5e2=5e3	19.7	ns		656	12923
5e3	58.5	1	699	656	38393
5e3		2	614		
5w2	6.2	12	564	564	3497
5s6	10.3	3	675	675	6953
Total area (ha)	305			**Farm total (tonnes)**	214463

* not sampled; # see Appendix 2

Table 3. Farm soil carbon stores in CO_2 equivalents on 'Stewarton' for 0-30 cm depth.

Map unit	Map unit area (ha)	Sample site No.	Carbon dioxide 0-30 cm (T/ha)#	Average Carbon dioxide 0-30 cm (T/ha)	Carbon dioxide in mapped unit 0-30 cm (T)
Stewarton					
Br	22.9	9	323	323	7397
Br-Ps	43.6	1	348	348	15173
Ca	65	4	742	674	43838
Ca		8	607		
Ca-Ps	180.9	2	425	487	88074
Ca-Ps		5	664		
Ca-Ps		17	371		
Ea=Br	2.8	ns*		323	904
Mq	49.1	14	207	207	10164
Mq-Ps	221.1	6	361	403	89104
Mq-Ps		7	321		
Mq-Ps		10	306		
Mq-Ps		11	624		
Ps-Ca	35.4	3	562	377	13330
Ps-Ca		15	191		
Ps	26.2	16	294	294	7703
Ps-Wk=Ps	11.3	ns		294	3322
gPs=Ps	22.6	ns		294	6644
Ps-Ea=Ps	9.6	ns		294	2822
Wk	33.5	13	234	234	7839
Wk-Ps	29.2	12	205	205	5986
Total area (ha)	753			**Farm total (tonnes)**	302300

* not sampled; # see Appendix 2

5.2 Scale of assessment of farm carbon storage

The farm carbon storage in the upper 30 cm of soils determined from broad scale data obtained from the ASRIS web site is compared with that determined at the farm scale in this study (Table 4). The storage values for 'Armidale' are the most similar, but the broad scale ASRIS value is 25% less than that determined from farm scale information. The difference for 'Ravenscroft' is 33% and for 'Stewarton' it is 82%. The differences are similar or much greater than those found by Frogbrook *et al.* (2009) who found differences of 8% and 45% for areas in Scotland and Wales respectively when comparing field survey data with information from the national UK database. The differences in this study are likely to be due to a number of factors including: soils mapped at the farm scale not included as components in the broad scale information; and attributed depth, soil carbon and/or bulk density values in the ASRIS data are derived from similarly mapped land system polygons which are not representative of soils on these specific farms. The discrepancies in this study are disturbingly large and indicate that the use of broad scale information within ASRIS, which is the Australian national database, can lead to large errors in calculating on-farm soil carbon storage.

Table 4. Farm soil carbon storage determined from ASRIS data and farm scale measurements.

Property Name	Area on property (ha)	Soil layer	Layer thickness (m)	Soil organic carbon (fraction)	Bulk density (T/m^3)	Carbon (T/ha)	ASRIS soil carbon (T CO_2e)	ASRIS farm soil carbon (T CO_2e)	Farm scale soil carbon (T CO_2e)*
'Armidale'	460	Layer 1	0.24	0.0205	1.4	68.9			
		Layer 2	0.06	0.008	1.40	6.7	127,512	127,512	170,454
'Ravenscroft'	42	Layer 1	0.13	0.0822	0.8	85.5			
		Layer 2	0.04	0.0455	1	18.2			
		Layer 3	0.13	0.0194	1.2	30.3	20,432		
	263	Layer 1	0.15	0.0583	0.9	78.7			
		Layer 2	0.15	0.0292	1.1	48.2	122,546	142,978	214,463
'Stewarton'	22	Layer 1	0.14	0.013	1.2	21.8			
		Layer 2	0.16	0.0037	1.3	7.7	2,339		
	696	Layer 1	0.14	0.0088	1.3	16.0			
		Layer 2	0.16	0.0011	1.4	2.5	47,161		
	38	Layer 1	0.14	0.013	1.20	21.8			
		Layer 2	0.16	0.0037	1.3	7.7	4,115	53,616	302,300

*data from Tables 1, 2 & 3

5.3 Impact of current and changed land management on soil carbon

The sequestration of carbon under current management from measured soil carbon values ranges from 0.13 T CO_2/ha/yr on Brumby soils on 'Stewarton' to 1.03 T CO_2 /ha/yr on Macquarie soils on 'Stewarton (Table 5). 'Armidale' (cropping) and 'Ravenscroft' (pasture) are modelled to be sequestrating carbon at 0.33 and 0.36 T CO_2/ha/yr respectively. The increases in soil carbon contents under current management (Figure 7) are relatively small and should be interpreted as indicating that current management is sustainable over the medium to long term in terms of soil carbon. The apparently small rates of sequestration on a per hectare basis are useful in accounting of carbon at the farm scale when multiplied by the area used for the particular land uses. For example, on 'Stewarton' an average rate of 0.34 T CO_2 /ha/yr amounts to 34 T CO_2 /yr for the 100 ha under cropping which may be off set against emissions generated by usage of fuel, electricity or fertiliser. A change in management from pasture to cropping on 'Armidale' (Figure 8) and 'Ravenscroft' (Figure 9) is modelled to result in a slight reduction in soil carbon content, which is not unexpected as the equilibrium between inputs and outputs will be altered with the inputs of carbon being less under cropping than under perennial pasture. A change in management from pasture to cropping on Macquarie soils on 'Stewarton' is modelled to result in an increase in soil carbon which also occurs on Brumby and Panshanger soils under current management. The consistent increase in soil carbon on 'Stewarton' across the 3 soil types, indicates that carbon inputs are greater than outputs and that the current mix of irrigated cropping, green manure crop, return of all cereal stubbles plus 30% of the time under perennial pasture or lucerne, is a sustainable management regime over the medium to long term in terms of soil carbon. Research over an 11 year period in the UK found rotations with 25% or less of pasture phase in combination with cereals and potatoes, resulted in a decline in soil organic carbon (Philipps 2001). Sites under arable agriculture have been found to reach stable or very slowly changing organic matter levels under continuous arable cropping regimes (Hatley *et al.* 2001). Once these equilibrium levels are reached, modern farming systems do not cause further decline in soil organic matter content.

The absolute changes in soil carbon percentage are relatively small and are unlikely to be measurable at the paddock scale over the medium term. Cotching and Sparrow (2005) found that sampling once every eight years in Tasmania is insufficient to track a trend, that data collected at a paddock scale is so variable that it is difficult to establish clear trends, or that there are many management factors contributing to changes in soil organic carbon that are not accounted for in an intermittent soil monitoring program. They found that over an 8 year period, adding a green manure crop to the rotation or including more years of pasture produced no consistent effect on soil carbon at the paddock scale.

The change in CO_2 values are three orders of magnitude (1000x) less than the calculated total soil carbon stores (Tables 1, 2 & 3) on 'Armidale'(371 T CO_2/ha), 'Ravenscroft' (702 T CO_2 /ha) and 'Stewarton' (401 T CO_2 /ha) respectively. This demonstrates that farmers are custodians of a large 'bank' of soil carbon which is susceptible to degradation and conversion into CO_2 if management is not sustainable.

The use of default soil carbon values in Black Magic is less than ideal as shown by the value for 'Armidale' being greater than that actually measured and that for 'Ravenscroft' being less. Use of the default values can reduce the annual change in CO_2 and may change it from negative to positive amounts.

Table 5. Black Magic model outputs of soil carbon contents and CO_2 change.

'Armidale'	Map unit			
	4w1		4s	
Current management	Cropping*	Cropping*	Pasture	
Future management scenario				Cropping[1]
Measured soil carbon (%) 0-20 cm	1.98		2.83	2.83
Black Magic default soil carbon (%)		2.50		
Modelled 100 year soil carbon	2.36	2.58		2.59
Change in CO_2 (T CO_2/ha/yr) (+ sequestration; - emissions)	0.33	0.07		-0.21
'Ravenscroft'	Map unit			
	3c1		4e5	
Current management	Pasture*		Pasture*	Pasture*
Future management scenario		Cropping[2]		
Measured soil carbon (%) 0-20 cm	6.27	6.27	5.51	
Black Magic default soil carbon (%)				3.50
Modelled 100 year soil carbon	6.77	6.10	4.99	3.89
Change in CO_2 (T CO_2/ha/yr) (+ sequestration; - emissions)	0.36	-0.12	-0.45	0.33
'Stewarton'	Soil type			
	Brumby	Panshanger	Macquarie	
Current management	Cropping*	Cropping*	Pasture*	
Future management scenario				Cropping[3]
Measured soil carbon (%) 0-20 cm	2.80	1.33	2.62	2.62
Modelled 100 year soil carbon	2.95	1.96	3.80	2.86
Change in CO_2 (T CO_2/ha/yr) (+ sequestration; - emissions)	0.13	0.55	1.03	0.200

*See Appendix 3; [1] cropping with no irrigation onto pasture phase; [2]processing potatoes grown 1 year in 5; [3] cropping using the same rotation as currently practiced

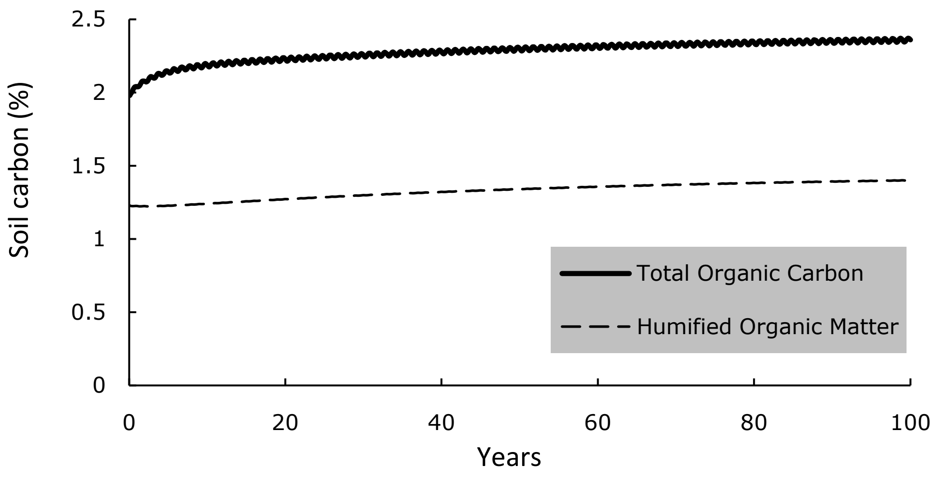


Figure 7. Modelled change in soil carbon for map unit 4w1 under current management on 'Armidale'.

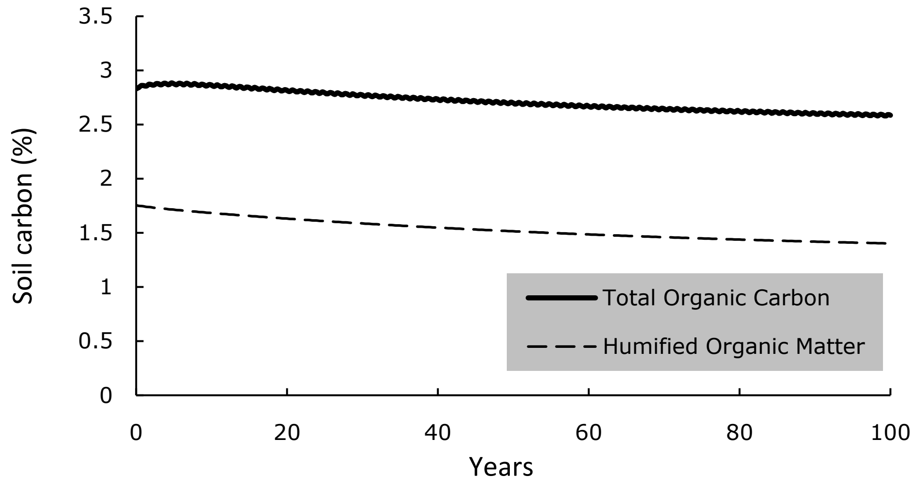


Figure 8. Modelled change in soil carbon for map unit 4s under a change in management from pasture to cropping on 'Armidale'.

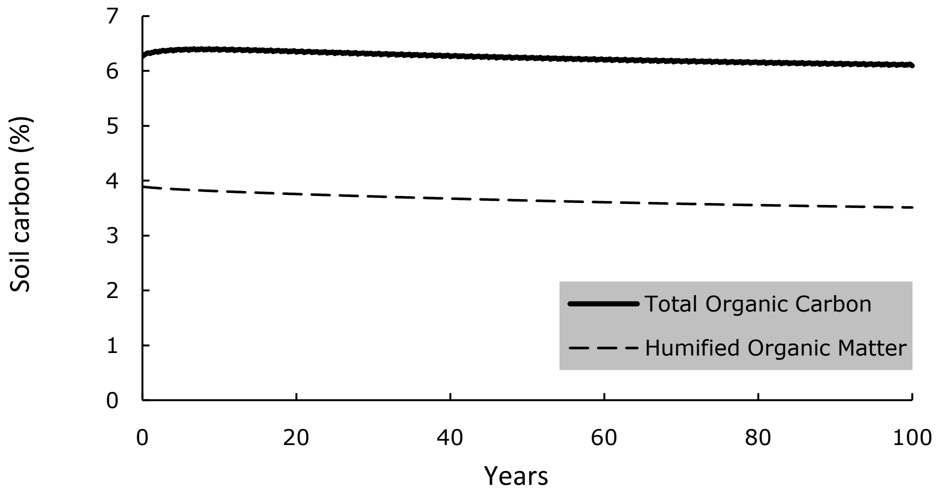


Figure 9. Modelled change in soil carbon for map unit 4s under a change in management from pasture to cropping on 'Armidale'.

5.4 Comparison of outputs from specific soil carbon sampling with outputs from agronomic soil sampling

The soil carbon contents for equivalent depths from paddocks with both agronomic soil test information as well as data collected specifically in this study are presented in Table 5.

Significantly different soil carbon results have been obtained in other Tasmanian research using Walkely-Black and LECO methodologies (McDonald *et al.* 2008). This may be caused by the reagent used in the standard Walkely-Black test running out at about 5.5% carbon. Normally when this happens, the sample is halved and re-tested, however, some laboratories may not be so meticulous in their methods. Consequently, values greater than 5.5 % in Table 4 were not used when comparing the differences between the two sets of data (Figure 10). There appears to be good agreement between the 2 sets of data (r^2 = 0.88) and there was no significant difference between the 2 means by Student t-test (P = 0.08).

Table 5. Soil carbon values from previous agronomic soil tests and corresponding sites sampled in this investigation.

Paddock	Depth (mm)	Year sampled	Corresponding sampling site	Soil test Carbon (%)	Proof of concept Carbon (%)*	Difference
Bill's	200	2009	12	1.03	1.4	0.37
Burnt House	150	2005	5	2.4	3.4	1
Dens Hill	100	Pre 2000	1	3.1	3.3	0.2
Forbes	100	Pre 2000	10	3.3	3.9	0.6
Hut	200	2009	6	1.7	2.7	1
Junction Marsh	100	Pre 2000	15	7.9	6.6	-1.3
Parkwater Marsh	100	Pre 2000	13	4.2	4.3	0.1
Peters	200	2009	8	1.3	1.9	0.6
River	100	Pre 2000	14	1.8	6.9	5.1
Road	200	1999	2	3.4	3	-0.4
Road	100	Pre 2000	2	5.5	4.9	-0.6
Sandstone Marsh	100	Pre 2000	16	4.6	8.6	4
Sandstone Marsh	100	Pre 2000	17	4.6	6.7	2.1
The Strip	150	2005	7	1.7	2.1	0.4

*Calculated by proportion of depth sampled

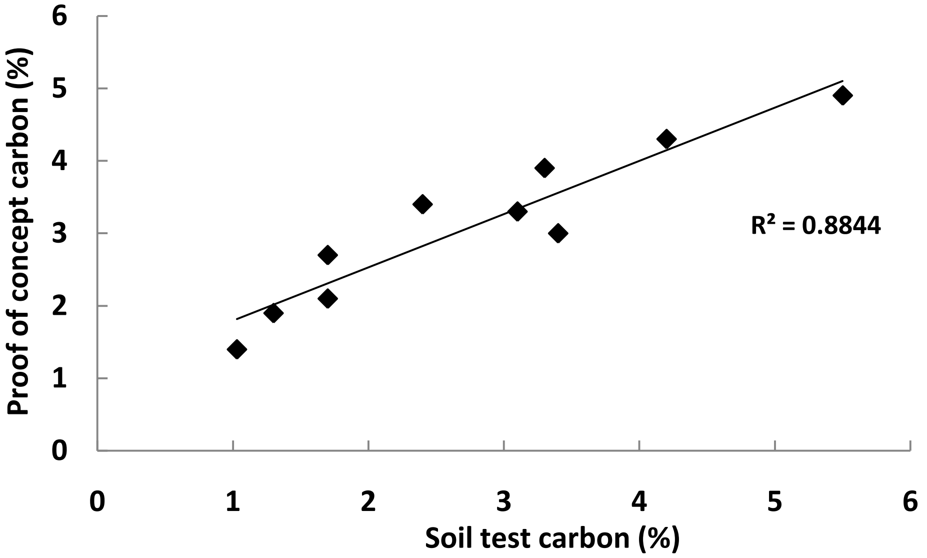


Figure. 10. Relationship between soil test and proof of concept soil carbon values for corresponding depths.

These results indicate that soil test values of carbon for soil carbon contents of 5.5 % or less obtained in day to day agronomic soil tests, are similar to those determined by more detailed sampling used in this study. Consequently, the agronomic soil test values are considered to be suitable for use in models such as Black Magic, as long as they are adjusted to corresponding depths before use.

Conclusions

The measured farm soil carbon stores were 371 to 702 T/ha CO_2 equivalents across the three farms assessed in this pilot. The highest value occurred on predominantly Red Dermosol and Ferrosol soils, which have high clay contents, are under perennial irrigated pasture for dairying, and have a mean annual rainfall of 1242 mm. The lower soil carbon stores occurred on Kurosols, Sodosols and Tensols which have sandy loam surface textures, are used for cropping and have mean annual rainfalls of 560 – 760 mm. The largest property (753 ha) and had the greatest soil carbon store (302,300 T CO_2 equivalents) but the smallest property (305 ha) had a greater soil carbon store (214,463 T CO_2 equivalents) than the 460 ha property (170,454 T CO_2 equivalents) due to a combination of soil type, land use and climate.

The total farm carbon stores are much larger (i.e. 1000 x greater) than modelled annual emissions or sequestrations. Modelling of the influence of management on soil carbon indicates that farmers can influence whether they emit or sequester soil carbon on an annual basis. This study demonstrates that farmers are custodians of a large ‘bank’ of soil carbon which is susceptible to degradation and conversion into CO_2 if management is not sustainable.

Agronomic soil test values of soil carbon contents less than 5.5 % were similar to those determined by more detailed sampling used in this study. Consequently, the agronomic soil test values are considered to be suitable for use in models such as Black Magic, as long as they are adjusted to depths used in the modelling.

The calculated farm carbon storage in the upper 30 cm of soils varied depending on the scale of investigation. Broad scale assessment using ASRIS information ranged from being 25 - 82% less than that determined from farm scale information. The differences are disturbingly large and indicate that the use of currently available broad scale information can lead to large errors in calculating farm soil carbon storage. The result is perhaps unsurprising given that the ASRIS data is of relatively small resolution. It must be emphasized that this study sampled three farms in the north and northeast of Tasmania. Additional sampling from other locations, where there are a range of soil types encompassing other land use types and topography, would further contribute to improving the estimates of the amount of carbon held on farms in Tasmania.

Acknowledgements

I wish to thank Rachel Brown and Duncan McDonald of Agricultural Resource Management for their assistance in conceiving and designing this project and for supplying the farm soil type area data. I also wish to thank the three pilot farm owners for allowing me to take the soil samples and for supplying details of their crop rotations and relevant soil analyses.

References

Doyle, R.B. (1993) Soils of the South Esk Sheet, Tasmania (southern half). Soil Survey Series of Tasmania, No. 1. Department of Primary Industry and Fisheries, Tasmania.

Chilvers, W.J. (2007) 'Armidale' Soil Management Plan, Carrick, Tasmania. Agricultural Resource Management, Tasmania.

Chilvers, W.J. (1998) Soils of 'Valleyfied' and 'Stewarton', Epping Forest, Tasmania. Agricultural Resource Management, Tasmania

WE Cotching, W.E., Sparrow, L.A. (2005) Changes over 8 years in soil organic carbon and pH on Ferrosols in northern Tasmania

Cotching, Bill (2009) Soil Health for Farming in Tasmania.

Eldridge, R. (1998) Land Capability Survey of the Ringarooma Valley. Department of Primary Industry, Water and Environment, Tasmania, Dorset Council and Natural heritage Trust.

Frogbrook, Z.L., Bell, J., Bradley, R.I., Evans, C., Lark, R.M., Reynolds, B., Smith, P. Towers, W (2009) Quantifying terrestrial carbon stocks: examining the spatial variation in two upland areas in the UK and a comparison to mapped estimates of soil carbon. Soil Use and Management **25**, 320-332.

Grose C.J. (1999) Land Capability Handbook. Guidelines for the Classification of Agricultural Land in Tasmania. Second Edition. Department of Primary Industries, Water and Environment, Tasmania, Australia.

Hatley DLJ, Garwood TWD, Johnson PA 2001. The impact of changing farming practices on soil organic matter and soil structural stability of Fen silt soils. In 'Sustainable Management of Soil Organic Matter' (Eds RM Rees, BC Ball, CD Campbell, CA Watson) pp.157-162. (CABI International: Wallingford, UK)

Jenkinson, D.S. (1990) The turnover of organic carbon and nitrogen in soil. Phil. Trans. R. Soc Lond. B **329**, 361-368.

Declan McDonald, Jeff Baldock, Darren Kidd (2008) Cradle Coast Organic Carbon Monitoring Trial. National Land and Water Resources Audit, National Monitoring and Evaluation Framework.

McKenzie, N.J., Dixon, J. (Eds) (2006) Monitoring soil condition across Australia. Recommendations from the Expert Panels. Prepared on behalf of the National Committee on Soil and Terrain for the National Land and Water Resources Audit.

Philipps L 2001. The effects of all-arable organic rotations on soil organic matter levels and the phosphorus and potassium status over the period 1987-1998. In 'Sustainable Management of Soil Organic Matter' (eds RM Rees, BC Ball, CD Campbell, CA Watson) pp. 294-300. (CABI International: Wallingford, UK)

Skjemstad JO, Spouncer LR, Cowie BA, Swift RS (2004) Calibration of the Rothamsted organic carbon turnover model (RothC ver: 26.3), using measurable soil organic carbon pools. *Australian Journal of Soil Research* **42**, 79–88.

Walkley, A., and Black, I. A. (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29-38.

Appendix 1. Details on the Black Magic carbon model

By Peter Rayner and Leigh Sparrow, Tasmanian Institute of Agricultural Research

1.0 Introduction

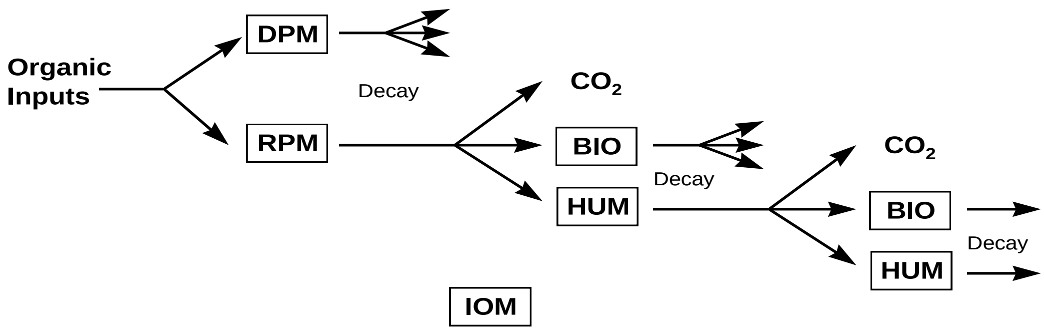
BlackMagic is a model of the dynamics of organic carbon in Tasmanian cropping soils. It calculates the input of organic matter from the individual crops in a rotation and determines the rate at which organic carbon is oxidised and lost from the soil as carbon dioxide gas. From a known starting point the model can predict future soil organic carbon content. The model contains a large database containing relevant parameters from thirty major crops, fourteen soil/area combinations and over 60 representative sets of climatic conditions.

The organic matter decomposition rates are based on those of the *RothC* model developed by *Rothamsted Research,* U.K.

Incoming organic carbon is initially split into two compartments, Decomposable Plant Material (DPM) and Resistant Plant Material (RPM). These compartments subsequently decay to produce Microbial Biomass (BIO), Humified Organic Material (HUM) and carbon dioxide that is lost to the atmosphere. Further decay of residual BIO and HUM results in each compartment undergoing further three way splits producing BIO, HUM and more carbon dioxide. Incoming plant material is divided between the first two compartments once only. Decomposition is calculated on a monthly basis.

The structure of the model is shown in Figure 1.

Figure 1 - Structure of the Rothamsted Carbon Model



RPM : Resistant Plant Material
DPM : Decomposable Plant Material
BIO : Microbial Biomass
HUM : Humified OM
IOM : Inert Organic Matter

Each of the four active compartments has its individual decomposition rate constant that is modified by temperature, moisture and the amount of soil coverage. A fifth compartment, Inert Organic Matter (IOM) (consisting mainly of charcoal) is considered to be very resistant to decomposition and remains at a constant level. Black Magic allows a choice of either traditional cultivation or reduced tillage practices (which reduce the rate of decomposition), and the option of irrigation is also included (which increases the rate of decomposition but simultaneously allows for increased inputs from higher crop yields). The model predicts future soil organic carbon content for any chosen crop rotation. The change in soil organic carbon is also displayed graphically along with the relative carbon contribution from the individual crops in the selected cropping rotation. In recognition of the increasing interest in the capacity of soil to sequester carbon and perhaps counter increasing levels of atmospheric CO_2, the model also displays changes in soil organic carbon in terms of CO_2 flux to and from the atmosphere.

2.0 Required Input

The model asks for the following information:-

2.1 Soil Type

A drop-down menu lists soil types as identified by Bill Chilvers in *Managing Tasmania's Cropping Soils, 1996*, and major cropping areas within Tasmania. Use the drop-down menu to select an appropriate soil type and area. Many alternate common names for soils may be found in the index.

This selection helps determine the default yield value for each crop subsequently entered. This selection also defines the soil clay content that is used to determine:-

The proportion of Resistant Plant Material that breaks down to CO_2
The moisture modifying factor

Soils are divided into five management types

2.1.1 Krasnozem Soils

Australian classification: Ferrosol

Krasnozems are reddish brown, strongly structured, gradational, clay loam to clay soils. A darker A-horizon indicates a surface accumulation of organic matter.

These soils are also known as Burnie clay loam, Yolla clay loam and Lapoinya clay loam.

2.1.2 Cressy Soils

Australian classification: Dermosol

Cressy soils are dark grey-brown to brown, loam to clay loam topsoils, overlying at about 150 mm depth a reddish brown to grey-brown rather friable clay on brightly coloured, mottled, brown clay.

2.1.3 Black Cracking Clays

Australian classification: Vertosol

Black cracking clays are black, structured, swelling clays overlying a mottled, greyish brown or strong brown sandy clay. The surface soil, of light clay or clay loam is thin and strongly self-mulching, developing a strong finely granular structure on drying.

These soils are also known as Canola, Roslyn, Churchill, Cranston, Laburnam, Dolerite and Basalt 1.

2.1.4 Duplex Soils

Australian classification: Sodosol

Duplex refers to the strong textural contrast between the sandy topsoil and a clay subsoil.

These soils are also known as Brumby, Woodstock, Brickendon, Newnham, Apricot, Richmond, Bridge, Riversdale, Coal, Strelly, Carrington, Nugent, Southfork, Enfield and Daisy.

2.1.5 Deep Sands

Australian classification: Tenosol

These soils have a deep, uniform sandy profile characterised by topsoils ranging from reddish brown to greyish brown. Topsoils show a slight accumulation of organic matter and weak structure.

These soils are also known as Panshanger, Invequarity, Penrise and Pines

2.2 Organic Carbon Content

If known, you should enter the organic carbon content of the soil and press *'Enter'*. If the organic carbon content of the soil is not known, leave this square blank – the model will assign a default value appropriate to the selected soil type. Note that carbon content, not organic matter content, is required. If you have a soil test showing organic matter content, divide this by 1.72 to get carbon content.

2.3 Minimum Tillage

If tillage between crops is minimised to maintain organic carbon levels check this box. When checked, a suitable small allowance is made to reduce organic carbon losses.

2.4 Meteorology

The drop-down menu allows the choice of about 60 representative farming climates in Tasmania. Select the appropriate one. This selection identifies monthly rainfall, evaporation and temperature data for the model. These data help establish the rate of loss of organic matter from the soil. They are not used to determine default yield values for crops.

The database holds data for the following stations:-

> Beaconsfield, Bicheno, Blessington, Bothwell, Bracknell, Bridport, Cambridge, Campania, Campbell Town, Cleveland, Colebrook, Cressy, Deloraine, Devonport, Elliott, Erriba, Exeter, Fingal, Flinders Is. , Flowerdale, Forth, Geeveston, Gladstone, Grove , Gunns Plains, Hagley, Hobart, Kempton, King Island, Latrobe, Launceston (Airport), Launceston (City), Lilydale, Longford, Marrawah, Meander, Mole Creek, New Norfolk, Nubeena, Oatlands, Orford, Pipers River, Port Arthur, Ringarooma, Sassafras, Scottsdale, Sheffield, Sheffield, Smithton, Sorell, St Helens, Strahan, Swansea, Tewkesbury , Tomahawk, Triabunna, Ulverstone, Waterhouse, Wesley Vale, Westbury, Winnaleah, Woodbridge, Wynyard and Zeehan

2.5 Simulation Period

The model graphs predicted soil organic carbon over 100 years. The model will also predict the soil organic carbon for shorter periods. Input the appropriate simulation period and press *'Enter'*.

2.6 Crop

Drop-down menus allow the selection of any of thirty crops. A maximum of ten crops is allowed in a rotation. A crop or pasture must be selected for each year it is grown in a rotation. If one crop is grown continuously, enter it once only. The model will assume that there is only one crop in the rotation and that this crop is repeated every year.

If however the rotation for example consists of four years of pyrethrum followed by five years of pasture you must enter each year of the nine-year rotation separately.

Crops may be chosen from the following:-

> Barley, Beans - Broad, Beans - Green Slicing, Broccoli, Brussels Sprouts, Cabbage, Canola, Carrots - Baby, Carrots - Standard, Cauliflower, Lucerne, Lupins, Green Manure (Oats), Green Manure (Ryegrass), Oats, Onions, Pasture (Grass), Peas - Field, Peas - Green, Poppies, Potatoes - Processing, Potatoes - Seed, Pyrethrum, Squash - Kabotcha, Swedes, Triticale, Turnips, Wheat,

2.7 Irrigation

Check this box for each irrigated crop. Irrigation increases the value of the default yield for those crops checked. It also increases the amount of soil moisture over summer. Irrigation increases the organic inputs but it also increases the rate of decomposition. The net effect can be negative or positive depending on the other parameters chosen.

2.8 From

A drop-down menu is used to select the month of sowing for each crop in the rotation. The month of sowing is used to calculate the length of a rotation and the fallow period.

2.9 To

A drop-down menu is used to select the month that represents the end of the growing season for each crop in the rotation. Usually this is the month of harvest. For potatoes enter the month that the tops die back rather than the month of harvest.
This month is used to calculate the length of a rotation and the fallow period.

2.10 Residue Management

Drop-down menus are used to select the appropriate residue management. You may choose between the following options:-

- Incorporated
- Grazed
- Grazed and baled for hay
- Mulched
- Left standing
- Burnt
- Removed

Your selection determines the percentage of the crop that is returned to the soil.

2.11 Yield
Yield, in tonnes per hectare, is an optional field. You may leave this blank or enter your expected yield. When very high yields are entered an alert message may be triggered. You may ignore this if you wish or adjust the value if necessary. Yield is one of the factors used to calculate the amount of organic material returned to the soil. When left blank, hidden default values are used to make this calculation. Area, soil and use of irrigation determine the default values.

3.0 Model Output
Output from the model is in the four forms listed below.
3.1 Rotation Summary
A summary of the rotation appears below the list of crops that are selected for the rotation. The summary includes the number of crops entered, the length of the rotation in years, the initial soil organic carbon as entered or the default value for the particular soil type entered and the predicted soil organic carbon after the chosen simulation period.
3.2 Hundred Year Graph
By pressing the button labelled *'Graph'* the Hundred-Year graph is displayed. The top line of the graph shows the predicted soil organic carbon levels for the next 100 years. Below it is a second line displaying the amount of carbon in humified material. Buttons are displayed that allow you to return to previous screen views.
3.3 Relative Contribution by Crop
The button labelled *'Crop'* takes you to a screen view displaying the relative contribution made by the crops chosen in the rotation. The crops appear in the order selected. All crops are shown to make a positive contribution as this is the relative amount of organic carbon contributed to the soil. It does not allow for the losses incurred during the growing period. Buttons are displayed that allow you to return to previous screen views.
3.4 Carbon Dioxide Flux
Changes in the amount of soil organic carbon result in carbon moving to or from the atmosphere as carbon dioxide gas. Carbon dioxide is a greenhouse gas implicated in global temperature change and consequently there has been considerable interest in the ability of soil to sequester atmospheric carbon. Carbon dioxide flux is displayed as tonnes of gas lost or gained per hectare. This is averaged over the simulation period.

Appendix 2. Soil carbon, bulk density and CO2 equivalent results

Site	Sample depth (cm)	Carbon (%)	Carbon (fraction)	BD core depth (cm)	wet wt (g)	dry wt (g)	container wt (g)	dry soil wt (g)	core vol (cm3)	Bulk Density (T/m3)	Carbon (T/ha)	Carbon dioxide (T/ha)	Weight carbon dioxide 0-30 cm (T/ha)
Armidale													
1	0-5	3.97	0.040	0-6	289.4	217.4	9	208.4	172.1	1.21	24.0	88.1	
	5-10	2.62	0.026	5-11	303.7	241.5	8.8	232.7	172.1	1.35	17.7	64.9	
	10-30	1.32	0.013	15-21	323.9	266.8	9.1	257.7	172.1	1.50	39.5	144.9	298
2	0-5	5.69	0.057	0-6	288	206	9.1	196.9	172.1	1.14	32.5	119.3	
	5-10	4.18	0.042	5-11	320.5	257.3	8.7	248.6	172.1	1.44	30.2	110.7	
	10-30	1.05	0.011	15-21	ns	ns				1.67	35.1	128.6	359
3	0-5	6.5	0.065	0-6	259.5	146.4	9.1	137.3	172.1	0.80	25.9	95.0	
	5-10	2.49	0.025	5-11	291.7	197.5	9	188.5	172.1	1.10	13.6	50.0	
	10-30	1.22	0.012	15-21	349.2	298.8	9.1	289.7	172.1	1.68	41.1	150.6	296
4	0-5	4.35	0.044	0-6	280	193	8.8	184.2	172.1	1.07	23.3	85.3	
	5-10	2.66	0.027	5-11	313.7	244.4	8.7	235.7	172.1	1.37	18.2	66.8	
	10-30	1.71	0.017	15-21	343.8	289	8.9	280.1	172.1	1.63	55.6	204.0	356
5	0-5	6.49	0.065	0-6	278	185.9	8.8	177.1	172.1	1.03	33.4	122.4	
	5-10	2.85	0.029	5-11	346.2	293.1	8.8	284.3	172.1	1.65	23.5	86.3	
	10-30	1	0.010	15-21	355	310.5	8.6	301.9	172.1	1.75	35.1	128.6	337
6	0-5	3.36	0.034	0-6	210.3	162.2	8.8	153.4	172.1	0.89	15.0	54.9	
	5-10	4.19	0.042	5-11	210.7	145.7	8.8	136.9	172.1	0.80	16.7	61.1	
	10-30	1.54	0.015	15-21	308.1	258.2	9	249.2	172.1	1.45	44.6	163.5	279
7	0-5	2.28	0.023	0-6	331.6	267.4	8.9	258.5	172.1	1.50	17.1	62.8	
	5-10	2.25	0.023	5-11	315	258.3	8.7	249.6	172.1	1.45	16.3	59.8	
	10-30	1.76	0.018	15-21	318.7	269.5	8.7	260.8	172.1	1.52	53.3	195.5	318
8	0-5	1.99	0.020	0-6	292.3	235.8	9.1	226.7	172.1	1.32	13.1	48.0	
	5-10	2.2	0.022	5-11	308.1	241.9	8.7	233.2	172.1	1.35	14.9	54.6	
	10-30	1.77	0.018	15-21	320.9	253.1	8.9	244.2	172.1	1.42	50.2	184.1	287
9	0-5	3.3	0.033	0-6	318.7	248.6	9	239.6	172.1	1.39	23.0	84.2	
	5-10	2.71	0.027	5-11	319.6	260.2	9	251.2	172.1	1.46	19.8	72.5	
	10-30	1.06	0.011	15-21	347.3	300.3	8.8	291.5	172.1	1.69	35.9	131.6	288
10	0-5	4.31	0.043	0-6	296	211.6	8.8	202.8	172.1	1.18	25.4	93.1	
	5-10	3.46	0.035	5-11	305.6	226.4	9	217.4	172.1	1.26	21.8	80.1	
	10-30	2.18	0.022	15-21	309	240.8	8.7	232.1	172.1	1.35	58.8	215.5	389
11	0-5	1.69	0.017	0-6	315.6	255.7	8.9	246.8	172.1	1.43	12.1	44.4	
	5-10	1.8	0.018	5-11	315.9	252.4	9	243.4	172.1	1.41	12.7	46.7	
	10-30	1.17	0.012	15-21	325.8	268.2	9.1	259.1	172.1	1.51	35.2	129.1	220
12	0-5	1.62	0.016	0-6	327.2	252.2	9	243.2	172.1	1.41	11.4	42.0	
	5-10	1.43	0.014	5-11	339.5	272.5	8.7	263.8	172.1	1.53	11.0	40.2	
	10-30	1.23	0.012	15-21	352.2	294.3	8.7	285.6	172.1	1.66	40.8	149.6	232
13	0-5	5.16	0.052	0-6	272.7	193.4	8.7	184.7	172.1	1.07	27.7	101.5	
	5-10	3.34	0.033	5-11	316.6	248.6	8.8	239.8	172.1	1.39	23.3	85.3	
	10-30	2.1	0.021	15-21	322.7	261	8.5	252.5	172.1	1.47	61.6	225.9	413
14	0-5	8.25	0.083	0-6	257.3	170.4	8.8	161.6	172.1	0.94	38.7	142.0	
	5-10	5.61	0.056	5-11	260.5	185.2	8.6	176.6	172.1	1.03	28.8	105.5	
	10-30	4.58	0.046	15-21	256.7	180.6	9	171.6	172.1	1.00	91.3	334.8	582
15	0-5	8.7	0.087	0-6	232.1	130.4	8.8	121.6	172.1	0.71	30.7	112.7	
	5-10	4.52	0.045	5-11	297.1	217.7	8.7	209	172.1	1.21	27.4	100.6	
	10-30	2.67	0.027	15-21	308.3	225.3	8.7	216.6	172.1	1.26	67.2	246.4	460
16	0-5	10.2	0.102	0-6	255.3	137.3	8.7	128.6	172.1	0.75	38.1	139.7	
	5-10	7	0.070	5-11	298.2	215.9	8.8	207.1	172.1	1.20	42.1	154.4	
	10-30	4.51	0.045	15-21	324.3	251.5	9.1	242.4	172.1	1.41	127.0	465.7	760
17	0-5	7.74	0.077	0-6	251.2	150.7	8.8	141.9	172.1	0.82	31.9	117.0	
	5-10	5.75	0.058	5-11	261.9	171.1	9.5	161.6	172.1	0.94	27.0	99.0	
	10-30	3.93	0.039	15-21	258.1	164.2	8.7	155.5	172.1	0.90	71.0	260.3	476
Ravenscroft													
1	0-5	6.94	0.069	0-6	248	144.7	9	135.7	172.1	0.79	27.4	100.3	
	5-10	5.61	0.056	5-11	286.4	204.8	9	195.8	172.1	1.14	31.9	117.0	
	10-30	5.02	0.050	15-21	296.2	233.9	8.7	225.2	172.1	1.31	131.3	481.6	699
2	0-5	9.84	0.098	0-6	238.5	148.5	9.1	139.4	172.1	0.81	39.8	146.1	
	5-10	6.58	0.066	5-11	271.1	205.4	9	196.4	172.1	1.14	37.5	137.6	
	10-30	3.95	0.040	15-21	266.7	204.7	8.6	196.1	172.1	1.14	90.0	330.0	614
3	0-5	10.8	0.108	0-6	251.7	147.9	9	138.9	172.1	0.81	43.6	159.8	
	5-10	7.4	0.074	5-11	293.5	212.9	9	203.9	172.1	1.18	43.8	160.7	
	10-30	3.93	0.039	15-21	290.1	220.6	9	211.6	172.1	1.23	96.6	354.3	675
4	0-5	7.55	0.076	0-6	264.2	174.8	9.1	165.7	172.1	0.96	36.3	133.2	
	5-10	5.74	0.057	5-11	273.1	206.6	8.8	197.8	172.1	1.15	33.0	120.9	
	10-30	3.68	0.037	15-21	279.9	228.6	8.9	219.7	172.1	1.28	93.9	344.4	599
5	0-5	7.57	0.076	0-6	274.8	183.6	9	174.6	172.1	1.01	38.4	140.8	
	5-10	5.81	0.058	5-11	283.8	221.6	8.8	212.8	172.1	1.24	35.9	131.7	
	10-30	3.97	0.040	15-21	293.3	231	8.5	222.5	172.1	1.29	102.6	376.3	649
6	0-5	8.68	0.087	0-6	304.4	212.1	8.7	203.4	172.1	1.18	51.3	188.0	
	5-10	6.53	0.065	5-11	314.7	252	8.7	243.3	172.1	1.41	46.1	169.2	
	10-30	4.79	0.048	15-21	305.5	248.8	8.9	239.9	172.1	1.39	133.5	489.5	847
7	0-5	9.99	0.100	0-6	258.5	167.8	8.8	159	172.1	0.92	46.1	169.2	
	5-10	8.14	0.081	5-11	280.1	214.1	8.7	205.4	172.1	1.19	48.6	178.1	
	10-30	6.55	0.066	15-21	278.2	218.2	8.8	209.4	172.1	1.22	159.4	584.3	932
8	0-5	10.2	0.102	0-6	266	160.1	9.1	151	172.1	0.88	44.7	164.0	
	5-10	6.07	0.061	5-11	268.9	195	8.8	186.2	172.1	1.08	32.8	120.4	
	10-30	5.28	0.053	15-21	264.7	195.9	9	186.9	172.1	1.09	114.7	420.4	705
9	0-5	9.45	0.095	0-6	251.4	137.6	9	128.6	172.1	0.75	35.3	129.4	
	5-10	6.08	0.061	5-11	288.8	202.7	8.8	193.9	172.1	1.13	34.2	125.6	
	10-30	4.08	0.041	15-21	291.9	214.8	8.8	206	172.1	1.20	97.6	358.0	613
10	0-5	8.22	0.082	0-6	234.2	135.5	8.8	126.7	172.1	0.74	30.3	110.9	
	5-10	6.05	0.061	5-11	279.5	203.7	9	194.7	172.1	1.13	34.2	125.5	
	10-30	3.78	0.038	15-21	288.3	221.4	9	212.4	172.1	1.23	93.3	342.0	578
11	0-5	9.84	0.098	0-6	253.4	149	9.1	139.9	172.1	0.81	40.0	146.6	
	5-10	6.8	0.068	5-11	270.1	182	9.1	172.9	172.1	1.00	34.1	125.2	

	10-30	5.26	0.053	15-21	279.4	206	9.2	196.8	172.1	1.14	120.3	441.0	713
12	0-5	9.35	0.094	0-6	231.2	114.9	8.8	106.1	172.1	0.62	28.8	105.7	
	5-10	6.31	0.063	5-11	269.3	177	8.7	168.3	172.1	0.98	30.8	113.1	
	10-30	4.19	0.042	15-21	286.8	202.1	8.7	193.4	172.1	1.12	94.1	345.2	564
13	0-5	8.43	0.084	0-6	255.4	166	8.8	157.2	172.1	0.91	38.5	141.1	
	5-10	6.15	0.062	5-11	264	193.1	8.4	184.7	172.1	1.07	33.0	121.0	
	10-30	4.3	0.043	15-21	260.7	215.2	8.7	206.5	172.1	1.20	103.2	378.3	640
14	0-5	12.3	0.123	0-6	238.8	136.1	8.6	127.5	172.1	0.74	45.6	167.0	
	5-10	10.4	0.104	5-11	242.5	161.2	9	152.2	172.1	0.88	46.0	168.6	
	10-30	7.79	0.078	15-21	239.4	163.4	8.8	154.6	172.1	0.90	139.9	513.0	849
15	0-5	15.6	0.156	0-6	237.9	127.2	8.7	118.5	172.1	0.69	53.7	196.9	
	5-10	12.7	0.127	5-11	250.5	175.4	8.7	166.7	172.1	0.97	61.5	225.5	
	10-30	8.68	0.087	15-21	252.8	177.1	8.7	168.4	172.1	0.98	169.8	622.7	1045
16	0-5	9.38	0.094	0-6	264.1	169	8.7	160.3	172.1	0.93	43.7	160.1	
	5-10	6.72	0.067	5-11	283.7	208.1	9	199.1	172.1	1.16	38.9	142.5	
	10-30	4.78	0.048	15-21	261.9	193.5	8.8	184.7	172.1	1.07	102.6	376.1	679
17	0-5	8.36	0.084	0-6	293.7	202.1	8.7	193.4	172.1	1.12	47.0	172.2	
	5-10	7.71	0.077	5-11	270.7	193.7	9.5	184.2	172.1	1.07	41.3	151.3	
	10-30	6.51	0.065	15-21	267.8	196.9	8.7	188.2	172.1	1.09	142.3	521.9	845
Stewarton													
1	0-5	4.67	0.047	0-6	283.3	216.2	8.6	207.6	172.1	1.21	28.2	103.3	
	5-10	2.72	0.027	5-11	293.8	234.5	8.8	225.7	172.1	1.31	17.8	65.4	
	10-30	1.36	0.014	15-21	362.4	318.5	8.8	309.7	172.1	1.80	48.9	179.4	348
2	0-5	5.73	0.057	0-6	251.1	171.4	8.7	162.7	172.1	0.95	27.1	99.3	
	5-10	3.77	0.038	5-11	261.6	191.1	9	182.1	172.1	1.06	19.9	73.1	
	10-30	2.61	0.026	15-21	299.4	236.1	8.6	227.5	172.1	1.32	69.0	252.9	425
3	0-5	8.99	0.090	0-6	248.4	144.8	9	135.8	172.1	0.79	35.5	130.0	
	5-10	6.93	0.069	5-11	268	178.1	9.1	169	172.1	0.98	34.0	124.7	
	10-30	3.79	0.038	15-21	288.3	198.7	8.5	190.2	172.1	1.10	83.8	307.1	562
4	0-5	6.44	0.064	0-6	250.7	170.3	8.7	161.6	172.1	0.94	30.2	110.8	
	5-10	6.71	0.067	5-11	253.4	183.8	9.1	174.7	172.1	1.01	34.0	124.8	
	10-30	6.4	0.064	15-21	269.3	194.6	8.8	185.8	172.1	1.08	138.2	506.6	742
5	0-5	8.03	0.080	0-6	253.6	154.2	9.1	145.1	172.1	0.84	33.8	124.1	
	5-10	6.9	0.069	5-11	252.3	164.8	8.8	156	172.1	0.91	31.3	114.6	
	10-30	5.76	0.058	15-21	268.1	182.3	8.8	173.5	172.1	1.01	116.1	425.7	664
6	0-5	4.52	0.045	0-6	271.7	211	9	202	172.1	1.17	26.5	97.2	
	5-10	3.29	0.033	5-11	257.6	208.9	8.9	200	172.1	1.16	19.1	70.1	
	10-30	1.78	0.018	15-21	309.2	264.7	8.7	256	172.1	1.49	52.9	194.1	361
7	0-5	3.66	0.037	0-6	288.1	208.9	9.6	199.3	172.1	1.16	21.2	77.7	
	5-10	3.54	0.035	5-11	289.5	215.9	9	206.9	172.1	1.20	21.3	78.0	
	10-30	1.52	0.015	15-21	322.5	264.5	8.6	255.9	172.1	1.49	45.2	165.7	321
8	0-5	5.28	0.053	0-6	262.1	199.7	8.7	191	172.1	1.11	29.3	107.4	
	5-10	4.99	0.050	5-11	258	199.4	8.8	190.6	172.1	1.11	27.6	101.3	
	10-30	3.91	0.039	15-21	312.8	247.6	8.7	238.9	172.1	1.39	108.5	397.9	607
9	0-5	6.27	0.063	0-6	280.9	187.6	8.7	178.9	172.1	1.04	32.6	119.5	
	5-10	3.47	0.035	5-11	292.2	236.3	9	227.3	172.1	1.32	22.9	84.0	
	10-30	1.25	0.013	15-21	305.9	233.2	8.8	224.4	172.1	1.30	32.6	119.5	323
10	0-5	4.41	0.044	0-6	270.6	187.7	8.9	178.8	172.1	1.04	22.9	84.0	
	5-10	2.76	0.028	5-11	276.5	205.9	8.7	197.2	172.1	1.15	15.8	58.0	
	10-30	1.35	0.014	15-21	352.6	293.4	9	284.4	172.1	1.65	44.6	163.6	306
11	0-5	6.58	0.066	0-6	281.4	201.7	8.7	193	172.1	1.12	36.9	135.2	
	5-10	2.41	0.024	5-11	279.8	228.3	8.7	219.6	172.1	1.28	15.4	56.4	
	10-30	3.56	0.036	15-21	334.8	293.6	8.7	284.9	172.1	1.66	117.8	432.1	624
12	0-5	2.75	0.028	0-6	289.3	222.7	8.7	214	172.1	1.24	17.1	62.7	
	5-10	2.31	0.023	5-11	271.7	220.6	9.1	211.5	172.1	1.23	14.2	52.0	
	10-30	0.79	0.008	15-21	308.9	277.6	9.1	268.5	172.1	1.56	24.6	90.4	205
13	0-5	2.44	0.024	0-6	251.4	195.3	9	186.3	172.1	1.08	13.2	48.4	
	5-10	2.05	0.021	5-11	279.1	211.4	9.1	202.3	172.1	1.18	12.0	44.2	
	10-30	1.22	0.012	15-21	332.8	281.9	8.9	273	172.1	1.59	38.7	141.9	234
14	0-5	1.97	0.020	0-6	239.8	205.4	8.8	196.6	172.1	1.14	11.2	41.2	
	5-10	2.36	0.024	5-11	251.8	214	8.7	205.3	172.1	1.19	14.1	51.6	
	10-30	1.03	0.010	15-21	301.6	269.6	8.9	260.7	172.1	1.51	31.2	114.4	207
15	0-5	1.84	0.018	0-6	307.8	249	8.8	240.2	172.1	1.40	12.8	47.1	
	5-10	1.89	0.019	5-11	296.9	238	8.6	229.4	172.1	1.33	12.6	46.2	
	10-30	0.79	0.008	15-21	344.3	300.3	9	291.3	172.1	1.69	26.7	98.0	191
16	0-5	3.57	0.036	0-6	248.7	189.2	8.8	180.4	172.1	1.05	18.7	68.6	
	5-10	2.76	0.028	5-11	253.8	213.5	9	204.5	172.1	1.19	16.4	60.1	
	10-30	1.6	0.016	15-21	285	251	8.9	242.1	172.1	1.41	45.0	165.0	294
17	0-5	3.58	0.036	0-6	297	234	8.9	225.1	172.1	1.31	23.4	85.8	
	5-10	3.16	0.032	5-11	289.3	226.8	9.1	217.7	172.1	1.26	20.0	73.3	
	10-30	2.17	0.022	15-21	304.4	238	9	229	172.1	1.33	57.7	211.7	371

Appendix 3. Management details used in Black Magic modelling

Property: 'Armidale'
Soil type: Duplex
Climate station: Hagley
Rotation:

Year	Crop	Grown from	Grown to	Stubble Management	Irrigated	Yield (T/ha)
1	Peas - Green	Oct	Feb	Grazed	yes	7
2	Green Manure (Ryegrass)	Feb	Oct	Incorporated	yes	Default
3	Beans - Green Slicing	Dec	Mar	Incorporated	yes	10
4	Poppies	July	Feb	Left Standing	yes	2
5	Wheat	Feb	Jan	Left Standing	yes	6.5
6	Triticale	Mar	Jan	Incorporated	yes	4
7	Poppies	July	Feb	Incorporated	yes	2
8	Pasture	Mar	Feb	Left Standing	yes	Default
9	Pasture	Mar	Feb	Left Standing	yes	Default
10	Pasture	Mar	Feb	Left Standing	yes	Default

Property: 'Ravenscroft'
Soil type: Krasnozem
Climate station: Ringarooma
Rotation:

Year	Crop	Grown from	Grown to	Stubble Management	Irrigated	Yield (t/ha)
1 - 10	Pasture(Grass)	Jan	Dec	Grazed	51%	6.5

Property: 'Stewarton'
Soil type: Duplex
Climate station: Campbell Town
Rotation: Pasture on Macquarie soils or the following rotation on Brumby & Panshanger soils

Year	Crop	Grown from	Grown to	Stubble Management	Irrigated	Yield (t/ha)
1	Poppies	Aug	Jan	Incorporated	Yes	4
2	Green Manure Oats	Feb	Sep	Incorporated		Default
3	Potatoes	Oct	Apr	Incorporated	Yes	70
4	Barley	May	Feb	Standing		5
5	Poppies	Aug	Jan	Incorporated	Yes	4
6	Barley	May	Feb	Standing		5
7	Pasture or Lucerne					Default
8	Pasture or Lucerne					Default
9	Pasture or Lucerne					Default